MONITORING SEDIMENT TRANSFER PROCESSES ON THE DESERT MARGIN**

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Summary

Landsat Thematic Mapper and Multispectral Scanner data have been used to construct change detection images for three playas in south-central Tunisia. Change detection images have been used to analyse changes in surface reflectance and absorption between wet and dry season (intra-annual change) and between different years (inter-annual change).

Change detection imagery has been used to examine geomorphological changes on the playas. Changes in geomorphological phenomena are interpreted from changes in soil and foliar moisture levels, differences in reflectances between different salt and sediments and the spatial expression of geomorphological features.

Intra-annual change phenomena that can be detected from multidate imagery are changes in surface moisture, texture and chemical composition, vegetation cover and the extent of aeolian activity. Inter-annual change phenomena are divisible into those restricted to marginal playa facies (sedimentation from sheetwash and alluvial fans, erosion from surface runoff and cliff retreat) and these are found in central playa facies which are related to the internal redistribution of water, salt and sediment.

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APPROACHES TO MONITORING DESERT MARGIN SEDIMENT TRANSFER PROCESSES

Sediment transfer processes at the desert margins are characterized by:-

1. high-magnitude and low-frequency events
2. a strong seasonality (which is often developed to such an extent on the desert margin that the dominant sediment transfer processes can change between seasons, notably between fluvial, in the wet season, to aeolian, in the dry season)
3. events which are often uncorrelated and spatially discrete (Brunsden & Thornes, 1979; Dott, 1983 and Schumm 1979)

Consequently geomorphological processes on the desert margin are difficult to monitor using conventional ground-based instrumentation because there is a very low probability of measuring any geomorphological event in a specific locality using site-specific instrumentation. However, the probability is increased if either the temporal or spatial dimensions are increased. The time dimension is inflexible for all practical monitoring purposes. Nevertheless processes can be monitored over a relatively short time period if a suitably large area is examined, thereby increasing the number of sites at which events occur during the monitoring period. One method of acheiving this is to utilize the synoptic capability provided by data from satellite sensors.

This approach is currently being evaluated in an area of south-central Tunisia (Fig.1) using data from the Landsat Thematic Mapper and Multispectral Scanner sensors for four major process domains - hillslopes, alluvial fans, braided rivers and playas. A preliminary visual study of multidate satellite imagery from the area indicates that geomorphological change can readily be detected. However, to effectively use the digital data provided by satellite imaging systems computer-assisted image processing techniques need to be utilized.

This paper is therefore concerned with evaluating the use of suitable image processing algorithms for the detection and monitoring of geomorphological change in south-central Tunisia. Data from the Landsat Thematic Mapper and Multispectral Scanner sensors, as well as the SPOT High Resoluton Visible sensor will be utilised. This paper presents the first observations from this project and concentrates on playa environments.

BACKGROUND TO THE STUDY AREA

Geomorphological Processes

Water plays a central role in the transfer of sedimentary materials in south-central Tunisia. The main components of the fluvial system on the desert margin area: i) Actively eroding montane drainage basins, ii) River channels, iii) Mountain front environments, and (iv) Closed depressions containing playas (known locally as chotts). It is clear that the transfer of sediment in, and between, these process-domains is a far from continuous process and episodic erosion and deposition prevail, often with long periods during which materials are stored in each component.

Aeolian activity is seasonally important, especially in the dry season from May to September (Table 1) when material is deflated primarily from the playa surfaces and redistributed onto adjacent mountain slopes, fields of small fixed dunes (nebkas), depressions, channels and onto the chotts. The aeolian deposits in the channels are then flushed through the system following runoff events. Fine grained material is also blown into the area from the S by dust storms late in the wet season.

Geology

The area includes both the highly folded Atlas Mountains to the N and the relatively undeformed Saharan Shield to the S. Detailed geological descriptions can be found for example in Burollet (1967). These two main areas are separated by the Saharan Boundary Fault and the northern area is still tectonically active (Coque & Jauzien, 1972).

Climate

The mean annual rainfall is low (80-157mm) and is mainly restricted to the period between September and May (Table 1). Temperatures and evaporation rates increase markedly in May, remaining high until late September. Runoff events are therefore mainly restricted to the wet season and streams are dry throughout the summer as there is no base flow contribution and soil moisture deficits are high. The climate is slightly more arid in the S (see for instance the records for Kebili, Table 1) where the mean annual rainfall is lower and consequently runoff events are rarer.

REMOTE SENSING AND DESERT GEOMORPHOLOGY

Previous Work

Remotely sensed data have been used for geomorphological investigations in arid and semi-arid areas by several workers and most applications have involved landform mapping (e.g. Mitchell et al., 1982; Sunha & Venkatachalam, 1982) or surficial material survey (Ashour, this publication; Asem et al., 1982; Bird et al., 1982; Davis et al., 1982; Townshend & Hancock, 1981). With the exception of Graetz & Pech (1982) and Klemas & Abdel-Kader (1982) few workers have attempted to monitor geomorphological change in these environments. Three problems are apparent from these previous studies:

1. They have been limited by the relatively coarse spatial resolution of the Multispectral Scanner sensor (79m). This situation has been improved by the finer spatial resolutions of the Landsat Thematic Mapper (30m) and SPOT High Resolution Visible sensors (20m and 10m), (Millington & Townshend, 1986).
2. They have been limited by the restricted spectral resolution of Multispectral Scanner data. The inclusion of middle infra red bands (1.55-1.75um and 2.08-2.85um) in the Thematic Mapper has greatly enhanced the possibility of discriminating between surficial materials (Bodechetel, 1983; Gladwell, 1982; Hunt, 1980; Kahle, 1984). These bands are crucial for any interpretation of sediment dynamics as it provides a potential

tool for the identification of river and fan gravel sources, duricrusted and varnished surfaces on fans and the accumulation of aeolian sand in channels and on playas.

3. The few geomorphological monitoring studies that have been undertaken in this environment using Landsat data have been severely restricted by availability of imagery. Archived imagery has been compared with current imagery (Klemas & Abdel-Kader, 1982) but change detection analysis based entirely on simultaneous image interpretation and ground verification has been far less satisfactory, (Graetz & Pech, 1982). This is because of the problems of obtaining large quantities of imagery due to the costs involved, ground station receiving policies and atmospheric conditions.

Change detection

Jones (1986a,b) and Munday (1985) have evaluated the potential of digitally processed Thematic Mapper and Multispectral Scanner imagery for geomorphological mapping in southern Tunisia. Whilst this research shows the application of single date imagery to mapping; monitoring geomorphological change using digital imagery requires the use of multidate imagery and different algorithms.

In this project, image data were supplied as computer compatible tapes and analysed digitally using an I^2S Model 75 image processor.

Any change detection study involves scene-to-scene image registration to ensure that pixels correspond to the same ground locations in each image. Six ground control points were used to co-register the Thematic Mapper quarter scene used in this study (Fig 2) with an average root mean square error of ± 0.37 pixels (equivalent to 11m on the ground), compared to twenty seven ground control points required to register the 512 x 512 pixel Multispectral Scanner images to an average root mean square error of ± 0.45 pixels (equivalent to 35m on the ground). This indicates the obvious advantage of Thematic Mapper imagery over Multispectral Scanner imagery in change detection studies. A nearest neighbour resampling procedure was used for the image registration in order to preserve the spectral values in the raw image data. The ground control points chosen in the co-registration procedure were permanent features such as road junctions, road/rail crossings, corners of well-defined plantations and points along sharply defined mountain fronts.

Slight misregistration of the imagery will produce errors in the change detection output image, since boundary pixels corresponding to one surface type may be compared with boundary pixels of an adjacent type, resulting in spurious change being detected.

Difference images were produced by subtracting the filtered image for the first date from that for the second date, and adding a constant to ensure that the output values were positive. Ratio images were produced by dividing the image for the first date by that for the second date. For the principal component analysis, the two images being compared were treated as one data set. In the principal components analysis Multispectral Scanner Bands 1 (0.5-0.6um), 2 (0.6-0.7um) and 4 (0.8-1.1um) were used, because of their widespread acceptance as a standard in false colour composite production. Previous research into the use of principal component analysis for change detection indicates that gross differences due to overall radiation and atmospheric changes are contained in principal component one, and that statistically minor changes associated with local changes in land cover appear in the higher order component images (Byrne et al., 1980; Lodwick et al., 1979; Richardson & Milne, 1983). Consequently principal components two and three were used to detect geomorphological change in this study. The use of principal components analysis for change detection is limited by the fact that the change detected cannot be attributed directly to changes in reflectance for a particular spectral band (Howarth & Boasson, 1983).

Various change detection algorithms have been applied to Multispectral Scanner data (reviewed by Nelson, 1983), but there has been little research using these algorithms in semi-arid or arid areas. Difference images, ratio images and principal components analysis images of the type described above were found to be the most useful for change detection in the study area. Vegetation indices (Howarth & Boasson, 1983; Singh, 1984) and the ratio difference technique were unsuccessful in detecting change in this environment, but were initially considered because of their success in temperate and humid-tropical environments. This is in part due to inherent sensor noise in each data set which is exacerbated when different data sets are ratioed. This problem was particularly evident on the ratio images obtained using Multispectral Scanner data, because it has a lower signal-to-noise ratio than Thematic Mapper data. The spectral bands providing the most useful information were the near infrared band (0.8-1.1um) of the Multispectral Scanner and the visible red (0.63-0.69um) and Middle Infrared (2.08-2.25um) band of the Thematic Mapper. All these bands provide information of vegetation and foliar and soil moisture levels. This indicates the importance of both geobotanical approaches to geomorphological interpretation of remotely sensed data, especially on the playa margins, and the moisture levels in surficial materials in interpreting patterns of sediment movement.

In the preliminary stages of this investigation, no attempt has been made to convert the digital numbers to absolute radiance values, or to correct for variations in sun angle and atmospheric scattering and absorption. Consequently there may be changes in the digital numbers between dates which are attributable to these variations rather than to real change. However these changes are relatively small in this area and for the datasets used have been excluded by using thresholds. The thresholds are confidence limits applied to the distribution of values produced by the change detection algorithms. Thresholds, chosen on the basis of previous research (Nelson, 1983; Singh, 1984), were applied to all change detection output images at $\pm$ 1 standard deviation (σ) from the mean value. False Colour Composites were produced by assigning the changes which corresponded to pixels with values of $<-1\sigma$ to the red gun of a colour monitor, those $>+1\sigma$ to the blue gun, and either the Multispectral Scanner Band 4 or Thematic Mapper Band 7 image to the green gun in order to preserve spatial detail.

GEOMORPHOLOGICAL MONITORING AND CHANGE DETECTION IN PLAYA ENVIRONMENTS

Geomorphological change detection has been approached in two ways in this project. Firstly, after changes have been identified by change detection algorithms on image pairs, the areas of change are retrospectively examined in the field. Whilst this allows a certain level of understanding of the type and magnitude of geomorphological processes in operation it is difficult to quantify the changes because of the lack of pre-change data. Secondly, monitored control sites have been established in each process-domain and these are examined after image acquisition, with the minimum possible delay. These sites provide a reference base for changes the might have occurred elsewhere in the study area and, if change occurs at these sites, quantitative measurements can be made.

Between January 1983 and April 1986 changes have been noted from change detection imagery constructed from Thematic Mapper data. The extent of these changes have varied significantly between process-domains (Table 2). The most change has been seen in the playas (65.3% by area) with very much lower amounts of change in the braided rivers, alluvial fans and other types of piedmont. The applications of the use of remotely sensed data in change detection in this paper will therefore concentrate on playas because of the larger amount of change that has been found in these environments during the first year of the project. To extend the length of the monitoring period Multispectral Scanner data dating back to 1981 have also been used. In addition SPOT High Resolution visible data has recently become available for the area and this has been incorporated in the study.

Environmental setting of playas

Three playas, Chotts el Djerid, el Fedjadj and el Guettar (Fig.1), have been intensively studied using remotely sensed imagery and ground observations. The Chotts el Djerid and el Fedjadj occur in a zone of subsidence to the S of the Atlas Mountains (Demaison, 1965) and they form part of a series of playas stretching from the Sebkhet Mechrecherma (25km to the NW of Gabes) to Chott el Melhrir (in central Algeria), (Fig.1). Chott el Djerid is the largest of these playas and covers about 5360km^2. It has an elongated north eastern arm, the Chott el Fedjadj, which continues E into the Sebkhet el Hamma, covering about 770 km^2. Their geomorphology and hydrology have been the subject of a number of investigations (e.g. Coque, 1962; Coque & Jauzien, 1967, Meckelein, 1977).

Chott el Guettar is about 75km^2 in area. It is situated in an enclosed basin bounded to the N by the Djebel Orbata and the S by the Djebel Berba. Both of these mountain ranges have active fans encroaching on the playa. The junction between the mountain front and alluvial fans on the Djebel Orbata marks the location of the Saharan Boundary Fault. Low ground and smaller mountains and hills are found to the E and W of the chott.

Geomorphological changes on the playas

Geomorphologically significant change has been detected on these playas from remotely sensed data during the period 1981-1986 and from ground observations at control sites.

These changes can be attributed to both surface and subsurface factors, in particular the seasonality of the hydrological regimes, surface salt dynamics, interactions with adjacent landforms and aeolian activity. These factors support the existence of seasonal patterns of climatically-controlled geomorphological change. Other geomorphological phenomena respond to fluctuations with shorter or longer periodicities than the seasonal patterns which are not necessarily related to climatic fluctuations. Geomorphological phenomena on playas can be grouped into facies defined by surface detail, salt content and moisture regimes. Change detection imagery provides information on the movement of facies boundaries, as well helping to explain the phenomena found in each facies.

Therefore geomorphological changes in playas can be divided into classes defined by their temporal and spatial characteristics. Three change classes have been defined (Table

3); these are similar to the types of geomorphic change identified by Neal & Ward (1967) in the USA. This classification is of fundamental importance because it recognises that specific types of change can be observed with different types of remotely-sensed data and at different time intervals between image acquisition, as distinct from those that can only be observed by ground-based techniques.

Intra-annual (seasonal) changes

Intra-annual (seasonal) changes on playas have been previously identified by Glennie (1970), Langer & Kerr. (1966) and Neal & Ward (1967) and are readily detected by change detection algorithms applied to remotely-sensed imagery from different seasons. Imagery corresponding to wet and dry seasons have been compared for all three playas and five types of geomorphological change, or changes in parameters affecting the geomorphology of the playas, have been identified (Table 3).

1. Surface Moisture and Vegetation Changes (Chott el Guettar)

Seasonal patterns related to surface moisture and vegetation change are best illustrated by examining change detection images of winter and summer Thematic Mapper imagery of the Chott el Guettar (Fig.2). The greatest changes are those related to the fan delta adjacent to the NW of the playa.

Surface cover of the fan delta ranges from moderately-well vegetated (30-35%) to poorly vegetated (<5%) and is dominated by halophytic succulents, in particular *Crassula* spp, *Limoniastium gyonianum*, *Limonium* spp., and slopes very gently towards the playa. On the fan delta there are a series spring pot and spring neck complexes (Reeves, 1965); these are sparsely vegetated, subdued depressions, which feed into rills, (Fig.3). They in turn drain into three main distal channels varying between 50 and 100m wide and 2m deep, that exit onto the playa. These channels form embayments between the fan delta and the playa. Elsewhere the fan-delta/playa boundary is marked by a cliff of up to 0.5m in height. This cliff cannot be seen on remotely sensed imagery but the distinct vegetation cover differences between the moderately-well vegetated fan delta and the more sparsely vegetated playa margin accurately locate the boundary (Fig.2).

The change detection imagery (Fig.2) indicates higher absorption in the middle infrared over most of the fan delta in winter than summer. This is inevitably by a combination of higher levels of soil and/or foliar moisture in winter and has been seen on other playa margins in the area (Epema, 1986). The distal channels and adjacent playas are characterised by higher middle infrared reflectance in winter than in summer. The high summer middle infrared absorption strongly indicates higher soil moisture levels for these areas even during the summer. Field observations of the sparsely vegetated depressions and distal channels, in September 1985 and May 1986, showed they are indeed very moist at the surface in both seasons. No surface runoff has been noted in either seasons. However, in May 1986 evaporation pools along flow lines in the channels were readily identifiable from patterns of fresh, friable salt crystals in salt efflorescences. Similar phenomena have been noted on playas in southern Tunisia by ground observation and radiometric measurements (Epema, 1986). Effloresence lasts for about a week after a rainfall or runoff event and indicates, in this case, recent surface water flow.

The high soil moisture levels in the spring pots and necks, distal channels and adjacent playa are in all likelihood due to a continued persistently high level of groundwater seepage to the fan delta from the intensively irrigated area around Gafsa, 16 km to the NW. The higher winter reflectance values appear paradoxical considering the increased surface flow but are probably related to the fact that because surface flow is intermittent, water evaporates between flow events leaving surface salt efflorescences, such as to those found in May 1986. It can be hypothesised from field observations and satellite image interpretations that near surface groundwater flows through the fan delta and seeps into the eastern part of the playa throughout the year. In winter the decreased evaporation and evapotranspiration rates and increased precipitation, recharge the groundwater levels and it seeps to the surface at the spring pots flowing through the spring necks and distal channels onto the playa There have been no direct observations of water movement at the spring pots; however they take the form described by Reeves (1965) for similar phenomena in Texas and because of their reflectance behaviour in the wet and dry season it must be assumed that water preferentially seeps to the surface at these points.

The area influenced by winter surface water and high groundwater seepage throughout the year forms a roughly semi-circular area with a southern lobe adjacent to the fan delta; it is about 20 km^2 in area. Similar patterns in winter surface water contributions to the playa were seen on change detection imagery derived from Multispectral Scanner data from 1981 and Thematic Mapper imagery of the 1985 dry seasonal and 1985/86 wet season.

The other areas contributing surface water to the Chott el Guettar appear to be far less important in magnitude. Increased winter surface and subsurface flow along the Oued el Rahr and Oued es Sedd systems to the E and NE respectively is visible (Fig.2). In terms of the areal extent of higher moisture levels it appears that much less of the playa is affected by these water sources than in the western playa. Water flowing onto, or seeping through, the alluvial fans to the N shows little seasonal variation on the imagery. This is probably due to a lack of surface flow in the years examined, the dominance of relatively constant groundwater seepage, or the 'filtering' effect of the El Guettar oasis. Most of the fans to the S of the playa also show a similar effect despite the lack of a vegetation 'filter', suggesting a relatively constant groundwater seepage. However, substantial changes in moisture levels in the SE of the playa were seen on 1981 change detection imagery (Fig.4).

There are few nebkas on the playa (4% of 23 sample sites) and little evidence of wind-blown sand or winnowing (13% of 23 sample sites). Therefore in the absence of significant aeolian transport, groundwater seepage and surface water control the transport of salts and sediments onto, and their redistribution within, the playa. As would be expected there is little evidence from the change detection images and field observations on four transects across the playa of seasonal variation in groundwater levels. Nevertheless, the main groundwater source to the NW generates higher seepage rates throughout the year than the other sources because of the intensive irrigation in the Gafsa Oasis and the larger 'catchment'. The main seasonal changes in surface water and near-surface moisture are related to winter runoff from the fan delta to the NE and, to a much lesser, extent the channels draining Guettaria.

A less frequent source of surface water is from the alluvial fans to the S. Surface runoff acts as the main transporting mechanism for sediment movement onto the playa and it is particularly important in the areas adjacent to the active fans to the S. In addition, there is an area of active gullying on fine-grained old playa sediments to the SW. These gully systems shows a well developed dendritic network. Although the gullies rarely exceed 1m in depth the headwalls and sidewalls all showed contemporaneous collapse features in May 1986, indicating geomorphological recent activity. Extensive areas of sparse vegetation cover and poor barley cultivation with much evidence of rilling and sheetwash feed water into these gullies from the S. They act as further important sediment source area. Sediment can also be transported from alluvial fans to the N, but fine sediment will mostly be filtered out in the oasis. It is unlikely that surface water flow from the E and NW have high sediment loads because of the low channel gradients, the fine-textured parent material and the short channel lengths. Most sediment therefore moves into the playa from the S forming a south-central depositional wedge which is recognisable in all change detection images as an area of lower summer reflectance (Fig. 2 & 4); this is due to the increased water holding capacity of the sediments resulting in high soil moisture levels in winter. Salt transport, unlike sediment transport, is related to both surface water and groundwater fluxes and it is likely to mirror the hydrological regimes more strongly than the sedimentation patterns. The analysis of change detection imagery and ground observations has allowed the establishment of a provisional model of the relationships between surface and ground water influences and sediment and salt fluxes on Chott el Guettar (Fig.5). This model is currently being tested by textural and chemical analysis of surface sediments and a continuing series of soil moisture measurements.

2. Surface texture, Surface composition and Aeolian Activity (Chott el Djerid)

Seasonal changes in surface texture, composition and aeolian activity are best developed on the Chott el Djerid. This is because salt facies, which are strongly related to surface morphological features (Langer & Kerr, 1966), are well developed on this playa (Munday, 1985). A transect of control sites is located at 1km intervals to the N and S of the Fatnassa-Degache Road at 1km sampling intervals, (Fig.6). The control sites occur in four of the morphological zones defined by Mitchell (1982):

1. Wind sculpted, areas with winnowing, nebkas and small yardangs.
2. Areas of thick salt crusts
3. Areas of blistered thin salt crust with polygonal folding.
4. Areas dominated by groundwater upwellings known as _ain_ (pl. _aioun_)

Uncorrected reflectance values at the control sites on the Chott el Djerid have been analysed for Thematic Mapper data for 6th Sept. 1985 and 6th April 1986, (Table 4). By far the smallest changes are found in the areas of the playa strongly affected by wind action (the mean difference of reflectance values is 11.6), (Table 4). The other three morphological zones in which control sites are located show far greater seasonal differences in reflectance. The values for the areas of thick salt crust and _aioun_ are similar (49.7 and 47.5, respectively), and the changes in reflectance in the areas of thin salt crust are marginally higher (53.8).

Within one month of data acquisition ground site descriptions and data were collected at each control site. These data are summarised in four categories - aeolian and fluvial activity, hydrological regime, salt regime and vegetation- (Table 5). The changes in ground phenomena at the control sites parallel the changes in reflection and absorption.

In the areas of the playa which are strongly affected by wind the location and density of the most frequent geomorphological features - nebkas, phreatophyte mounds (mainly around Tamarix gallica) (Glennie, 1970), small yardangs in old playa sediments (Besler, 1977), areas of winnowing, fluting and other areas of sand accumulation - remained constant between September and May. The wind affected area is topographically higher than the playa facies to the W in which salt crusts and aioun are found. Consequently, the area was not extensively flooded in the 1985-86 winter and in May standing water was absent. Nevertheless, field evidence from May 1986 showed that standing water accumulated in the depressions between nebkas during the wet season. Many of the sand-rich nebka tails, which are dry and have the classical aerodynamic smooth or slightly rippled form in summer, displayed a "flight of small steps" (1-3cm in height) around them in May. The regularity and frequent occurences of these steps combined with fresh salt effloresences on nebka tails and in the depressions suggests they undergo partial solution by standing water in the wet season. Solution is not complete as they are still seen on the field in a partially dissolved state in late winter and on the borders between the Chotts el Djerid and el Fedjadj extensive nebka fields were visible on both summer and winter remotely sensed imagery. Similar evidence of the preservation of the form of geomorphological features on playa surface when flooded, have been noted by Glennie (1970), Hardie et al., (1978), Larger & Kerr (1966) and Reeves (1965). The steps only remain in the nebka tails until the sand dries out to such an extent that cohesion is lost or the thin crusts are destroyed by saltating soil grains (Watson, 1983), the steps collapse and the aerodynamic aeolian form once again dominates.

The greatest changes in ground phenomena where noted in the control sites located in the thin salt crust facies. Neal & Ward (1967) have also recognised the very dynamic nature of salt crust surfaces in American playas. Changes were noted in 71.4% of the control sites (Table 5). The thin salt crusts on the Chott el Djerid are dominated by halite (41.4-94%) and variable amounts of quartz (1.9-33.4%), low amounts of gypsum (usually <4%). The soluble salt content ranges from 8.7-37.7% and the dominant size fractions are very fine sand, silt and clay (Munday, 1985). The changes were almost all concerned with the level of salt crust development (ie. blistering, polygonal folding and cracking). The most constant features in the control sites in this facies were surface moisture levels and salt efflorensences. Some of the control sites when examined in May 1986 had a clean, highly reflective thin featureless salt crust varying from 0.1-1.0cm in thickness. Other sites had standing water to a depth of a few centimetres (Table 5). The resultant range in reflectance values is therefore quite high. As the water evaporates the salts accumulate at the surface in response to evaporation and the crust becomes slightly thicker until, by the late summer, it ranges from 0.3-1.5 cm at the control sites. More importantly, the surface microrelief increases with blistering and polygonal patterns of folding and cracking, developing in response to the planar isotropic positive (compressed) stresses established during the drying out of the crust (Christiansen, 1963). This increase in surface relief could not cause such a dramatic increase in reflectance (Table 4) and is most likely attributable to the absence of standing water and dessication of the salt crust in the summer.

The areas of thick salt crust and aioun show slightly lower changes in reflectance values than the areas of thin salt crust, but are far higher than the changes in the wind-dominated facies. Changes in surface phenomena at the control sites were variable. In the areas of thick salt crust field observations indicated that 81.0% of the control sites displayed changes, a similar proportion to those sites in the thin salt crust facies. However, none of the sites in the area of aioun showed significant changes in surface phenomena between the two observation periods. The thick salt crusts have a similar chemistry to the thin salt crusts. Halite varies from 45.0-97.4%, quartz from 0-50.0% and gypsum from 2.6-5.9%. The soluble salt contents are higher, varying from 25.9-41.5% (Munday, 1985). Field data from 1984 showed that the main salts in areas of thrust polygons were sodium (44-3400 me/l) and calcium (43,5-162 me/l) with lesser amounts of potassium (7.5-31 me/l). The texture of thick crust is coarser than the thin crust with greater proportions of medium and fine sand. Changes in the sites in the thick salt crust facies were dominated by the level of crust development. Less important factors included surface winnowing, crust blistering and polygonal cracking, the development of polygonal thrusting, standing water and flow features.

Inter-annual changes

Inter-annual changes have been identified from change detection images of single date images taken at similar times, but in different years. Satellite orbits and problems of image acquisition means that it is almost impossible for imagery of the same day and week to be acquired. Imagery acquired during the same month is feasible, especially in the dry season at the desert margin, but it is more difficult to obtain in the wet season because of increased cloud cover. Changes detected from these images should ideally distinguish between areas of longer term changes and stability.

Longer-term changes noted in the study area are divisible into two groups. Firstly, processes with an annual incremental adjustment due to seasonal variations in the rates of operation of geomorphological processes. These are subdivided into playa marginal processes, which are strongly influenced by the geomorphological and hydrological processes of the adjacent areas (Hardie et al., 1978; Reeves, 1968), and processes operating in the central playa facies, which are mainly internal adjustments to the water, salt and sediment budgets. Secondly, processes which occur less frequently (ie. high magnitude - low frequency events) which are linked to long return period storms or tectonic activity.

1. Changes in playa margins

The marginal processes that have been detected in the field on the Chotts el Guettar and el Fedjadj are mainly incremental marginal processs which operate each wet season e.g. cliff retreat, rill erosion and sedimentation. The resulting annual geomorphological change, from the cumulative effect of these processes in any one season, is relatively small. Consequently detection of these erosional and depositional processes is unsuccessful using remotely sensed data unless the interval between image acquisition is very short. These processes are not dealt with in this paper.

However sedimentation from alluvial fans onto playas is dependent on discharge events with long return periods and therefore they are high magnitude - low frequency events. The resultant sedimentation can easily be seen on single date remotely-sensed imagery (Fig.7). However, the length of time needed between image acquisition to detect these events on change detection imagery is obviously variable.

2. Changes in central playa facies

In the central playa facies two phenomena related to salt and sediment redistribution have been identified from remotely sensed imagery. These phenomena are mainly related to surface water movement and, to a much lesser extent, groundwater seepage. They occur on all the playas with control sites but are best developed on the Chotts el Djerid and el Fedjadj.

Winter runoff from surrounding higher ground gathers on the Sebkhet el Hamma (Fig. 8) each wet season and then flows westwards into the Chott el Fedjadj along very low gradients. Well developed geomorphological features related to these flow patterns are found in areas where the playa is narrow and, two areas have been studied in detail. Firstly, in the western Sebkhet el Hamma an inland delta to the N and a large, mobile sand body to the S constrict the playa to a width of about 2.5km wide (Fig.8). Secondly, the central Chott el Fedjadj is constricted by a 2m high cliff to the N and the Djebel Klikr, a 180m high gypsum hill, to the S. Here the playa is less than 2km wide and mainly unvegetated. Field observations made in May 1986 found much evidence of recent fluvial erosion of small pheatophyte mounds, scoured channels (Fig.9) and ripple marks in these two areas. In the first area there are 4 main channels and the downstream gradient of the widest channel is 0.16 in the second area there is only one channel with a gradient of 0.007 these flow features represent zones of relatively fast water flow for a playa environment and are areas of actively eroding playa sediments.

In the thin salt crust facies on the Chott el Djerid lines related to surface water flow (which are up to 0.5km wide) with splays at their ends can be seen as patterns in the salt crust (Fig.10). The form of these patterns in the salt crusts suggests strongly they were formed by surface water movement and along some of the "flow lines" darker "flow lines" can be seen suggesting more than one flow event. They terminate in splays which indicates flow into a slight depression. These are morphologically similar to the playa grooves which have been seen on other parts of the Chotts el Djerid and el Guettar and are also described by Reeves (1968) from Texas and Bonython & Mason (1943) from Australia. The imagery shows that at the splayed ends of the 'flow lines' that the uppermost crusts overlap other crusts, or salt-rich zones, beneath them (Fig.10), suggesting, once again, multiple flow events.

The playa surface to the S. of the road has become increasingly wetter over the past 3 years and at the present time standing water occurs throughout the year. The build-up of surface water is related to the recent road construction. The depth of the water table below the playa surface to the N is up to 0.57m higher than to the S. This is due to runoff from the mountains to the N. of the playa and very shallow groundwater, both of which flow southwards to a depression. Water ponds up to the N of the road because of the reduced transmissiability of the sediments compacted under the road. After the flow under the road they rise up to the surface. The resultant standing water then flows along very slight surface undulations (playa grooves) to a depression forming 'flow line' structures in the salt crust. The water flows around the aioun, which occur in the crust in this area, and furthermore water rising up at the aioun joins the southward surface flow.

CONCLUSIONS

Two categories of geomorphological change have been detected on the three playas examined in this study from remotely-sensed data (Table 3). These have been termed intra-annual and inter-annual changes. A third category of geomorphological change-sub-pixel change - cannot be detected from currently available remotely sensed data because of the spatial resolution of the sensor and the length of the repeat times due to the satellite orbits. Current and projected developments in satellite and sensor technology mean however that some types of geomorphological change now falling in the sub-pixel category will be able to be monitored by remotely sensed data in the near future.

This initial assessment of the use of remotely-sensed data to monitor episodic geomorphological processes on the desert margin suggests strongly that the method is of use to geomorphologists, hydrologists and sedimentologists. An analysis of the changes detected over the period 1983-1986 (Table 2) has shown that geomorphological change which can be detected by remotely sensed data has occured in three process-domains.

However only in one of these, the playa process-domain, would the probability of detecting change by ground-based monitoring equipment stand any reasonable chance of success. Over the past three years the playas have shown a large capacity for geomorphological change and change in parameters affecting geomorphological processes. The dynamic nature of playa geomorphology has previusly been recognised in the western USA (Neal & Motts, 1967) and the results obtained so far in this study concur with their observations. Some of the braided rivers in the study area have exhibited shifts in channels but others have shown no change detectable on remotely sensed imagery during the same time period. Activity on the alluvial fans and other piedmont types has been restricted to only a few areas and most, but not all, of the change detected can be directly attributed to seasonal vegetation differences.

A variety of change detection algorithms for remotely sensed data have been evaluated in this study and difference images, ratio images and principal components analysis have been found most useful. Spectral information for Multispectral Scanner Band 7 and Thematic Mapper Bands 3 and 7 were found to contain the most useful spectral information when analysing change on playas due to their ability to provide data on soil and foliar moisture levels and in the case of Thematic Mapper Band 7 variations in sediment mineralogy.

The important role of surface water in salt and sediment movement onto, and redistribution within, Tunisian playas is strikingly evident in this study. In many of the playa facies it appears to be equally, if not more, important than groundwater variations on an intra-annual basis. Furthermore, interactions with adjacent landforms and the role of aeolian activity are also locally important.

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FIGURE CAPTIONS

1. Location map. The Thematic Mapper quarter scene used in this analysis is indicated by a poecked line; the control sites are indiacted by .

2. Change detection image of Chott el Guettar produced by ratioing Thematic Mapper 2.08-2.25um data of January 1983 with September 1985; El Guettar oasis is indicated (EG). The areas of highest surface moisture change can be readily identified - the spring pots and necks on the fan delta (A); Guettaria (B); the area of high summer moisture levels on the playa related to groundwater discharge from the Gafsa Fan (C). The gullied areas in the south west can also be seen (D).

3. A spring pot, with rills in the spring neck beginning in the foreground, on the fan delta to the SW of El Guettar.

4. A third principal component image of Chott El Guettar Multispectral Scanner data from the wet and dry seasons of 1981. Areas with high levels of moisture change can be seen on one of the fans to the S of the playa and on the south-central playa. This area of change is related to deposition of eroded sediments from the fans.

5. Chott El Guettar: provisional model of seasonal water, salt and sediment dynamics.

6. SPOT High Resolution Visible scanner image of the northern Chott el Djerid. The Fatnassa-Degache road can be seen traversing the playa; the control sites are located at 1km intervals to the N and S of the road. The four morphological zones (see text) can be identified: (A) The wind sculpted areas with winnowing, nebkas and small yardangs; (B) Areas dominated by aioun; (C) Thick salt crust areas, and (D) areas of blistered thin salt crust with polygonal folding.

7. Landsat Thematic Mapper (right) and SPOT High Visible Resolution scanner (left) false colour composites from 1983 and 1985 respectively showing sedimentation of alluvial fan material onto the northern Chott El Djerid from a fan flanking Djebel el Asker. There has been little change in the small fan sediment in the time between image acquisition.

8. Landsat Multispectral Scanner False Colour Composite image of the Sebkhet el Hamma from 1981. The detail in the chott has been increased by contrast stretching the playa at the expense of the surrounding areas, but the town and oases of El Hamma (EH) can still be seen. Vegetation and salt patterns relating to surface water flow from the surrounding uplands is seen funnelling through the neck of the sebkhet as it enters the Chott El Fedjadj to the W.

9. Channel scoured by surface runoff in the central Chott el Fedjadj, the channel gradient here is 0.007.

10. SPOT High Resolution Visible False Colour Composite image of the central Chott el Djerid, March 1986. Two features are noticeable (i) the variable size of the aioun in the E of the image and (ii) the "flow-lines" (playa grooves) formed in the thin salt crusts which channel water on the salt crusts to a depression to S which terminate in splays.

Table 1 Climatic information for study area

	Kebili	Gafsa		El Guettar
Altitude (m)	56	314		268
Latitude (N)	$33^{\circ}20$	$34^{\circ}25$		$34^{\circ}20$
Longtitude (E)	$8^{\circ}58$	$8^{\circ}49$		$8^{\circ}55$
Temperature				
Mean annual ($^{\circ}$C)	21		19	
Min. mean ($^{\circ}$C)	3		4	
Max. mean ($^{\circ}$C)	42		38	
No. of Scirocco days	38		35	

Rainfall (mean annual, mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Gafsa & El Guettar	17	13	22	17	12	7	2	5	14	18	18	14	157
Kebili	12	8	16	9	5	1	0	0	4	8	15	10	80

For sites locations see Fig. 1

Table 2 Change detected in different process-domains between January 1983 and April 1986 from Thematic Mapper imagery for a $108km^2$ study area in south central Tunisia.

Major process-domains	Area, on quarter scene analysed (Km^2)	Area in each category with with +ve or +ve change (Km^2)	Proportion showing change (%)
Alluvial fans	359.0	29.8	12.05
Other types of pediments *(1)	4436.8	251.2	17.66
River channels(2)	262	66.1	25.32
Playas	2150.0	1403.2	65.23

Pediment types are based on work by K.A. White (Univ. of Reading)

(1) includes planated alluvial pediments, fan aprons, bajadas and alluvial plains

(2) measurements refer to lengths of channel, not areas.

Table 3. Classification of geomorphological change on Tunisian chotts

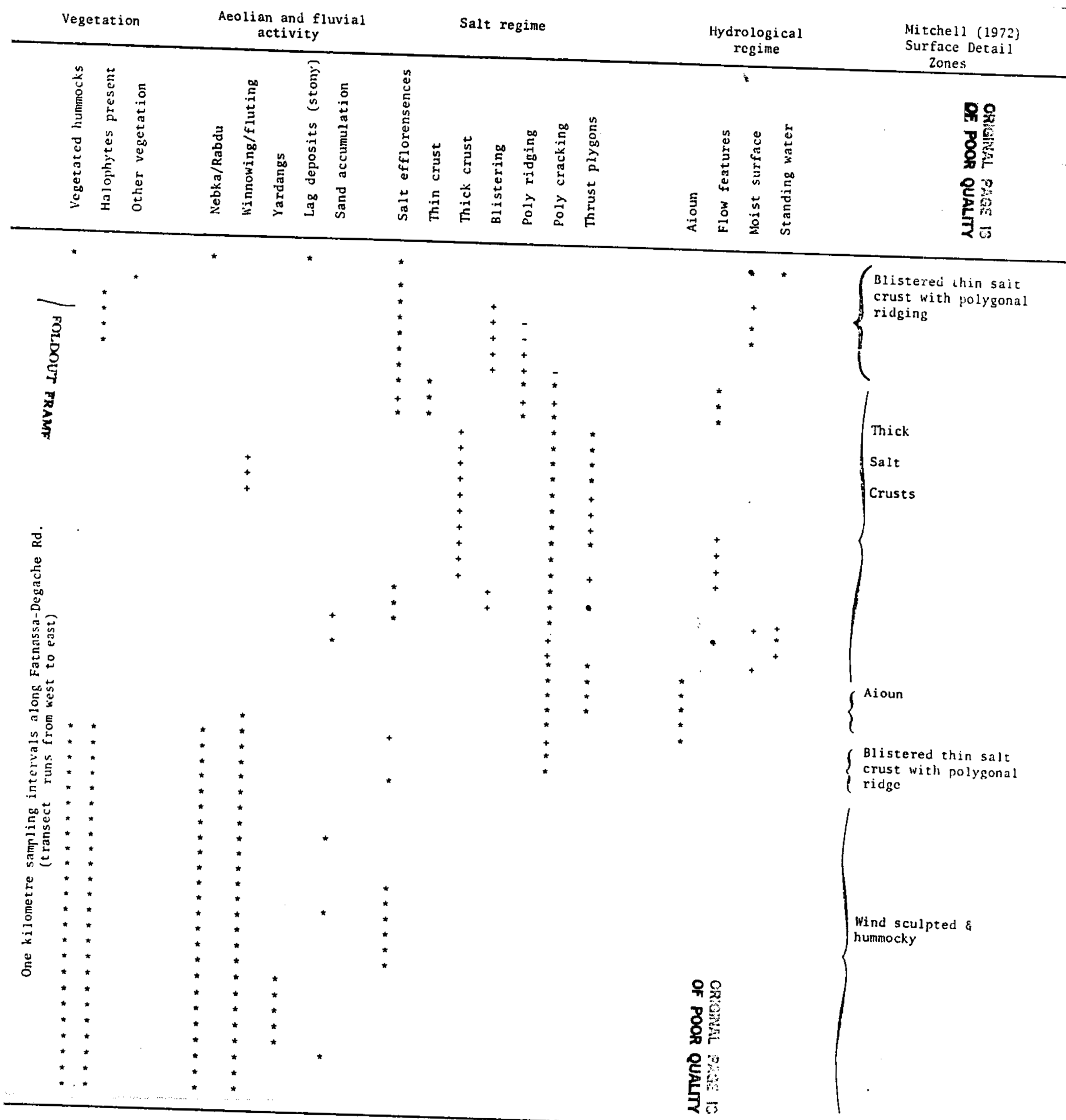
Change category	Relationship to satellite imagery	Characteristic types of change
Sub-pixel	Less than spatial and temporal resolution of imagery	Not considered in this paper
Intra-annual	Detected on multidate imagery from different seasons	1. Surface moisture 2. Surface texture 3. Surface composition 4. Vegetation cover 5. Aeolian activity
Inter-annual	Detected on anniversary imagery	<u>Marginal chott facies</u> 1. Sedimentation (a. sheetwash) b. alluvial fans 2. Erosion (a. runoff) (b. cliff retreat) <u>Central chott facies</u> 3. Surface water flow

Processes in parentheses often fall into the sub-pixel change category

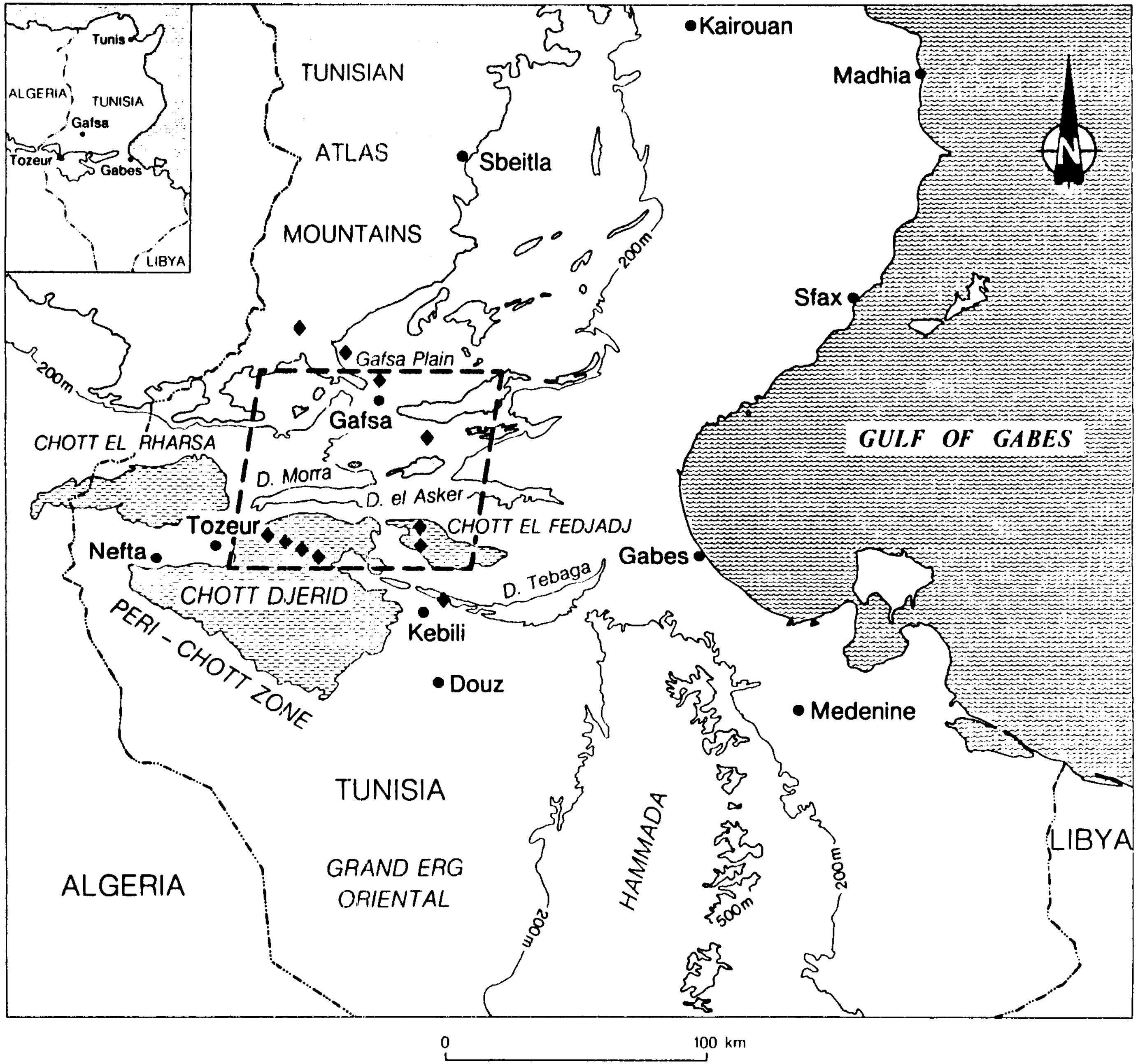
Table 4. Summary of reflectance data for control sites, by facies, in the Chott el Djerid

	Playa facies			
	Blistered thin salt crust with polygonal ridging	Thick salt Crust	Aioun	Wind-sculpted and hummocky
N =	14	42	10	40
<u>Data from control sites to N. of Fatnassa-Degache Road</u>				
Sept. 1985				
- Max DN	134	124	74	98
- Min DN	85	32	43	63
April 1986				
- Max DN	90	82	131	92
- Min DN	60	22	81	42
Differences				
- range	25-74	5-82	30-78	(-7) -45
- mean	52.1	46.1	55.6	13.7
<u>Data from control sites to S of Fatnassa-Degache Road</u>				
Sept 1985				
- Max DN	145	145	60	93
- Min DN	82	42	25	65
April 1986				
- Max DN	75	85	100	82
- Min DN	47	17	78	55
Differences				
- range	26-84	(-7) -78	25-46	(-7) -34
- mean	55.4	48.8	43.8	9.5
Mean difference in reflectance (all sites combined)	53.8	47.5	49.8	11.6

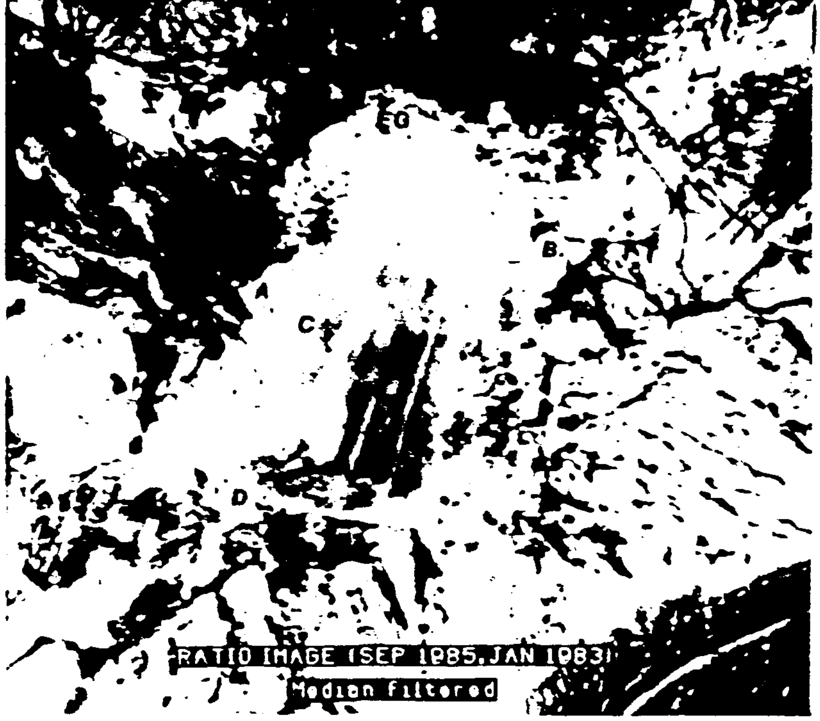
Table 5 Chott el Djerid: Changes in geomorphological, hydrological and ecological phenomena at 1km sampling intervals along the Fatnassa-Degache road. Observations were made in September 1985 and May 1986



* Feature present in winter, wet and summer, dry season
\+ Feature present in summer, dry season only
@ Feature present in winter, wet season only



OF POOR QUALITY


E
B
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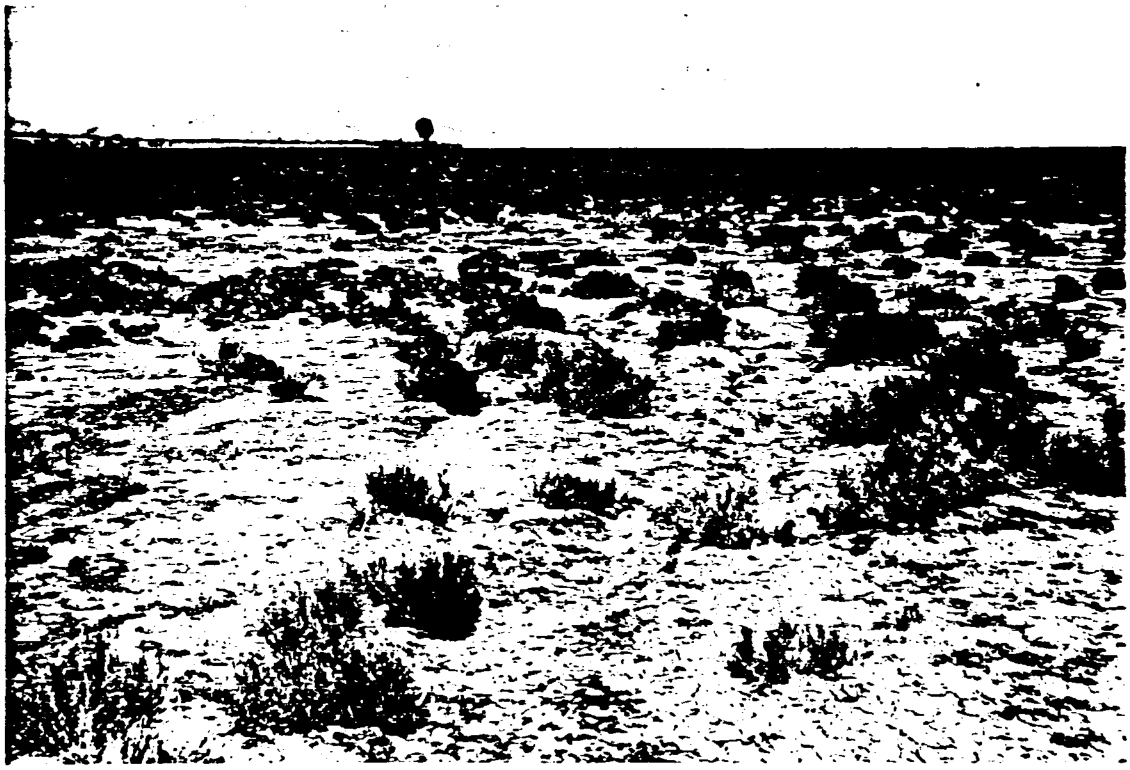
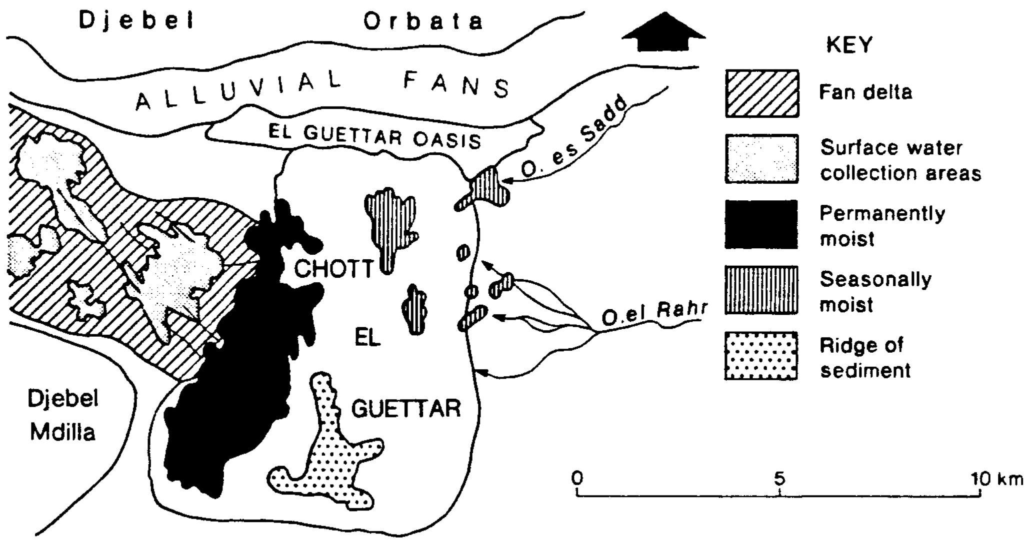
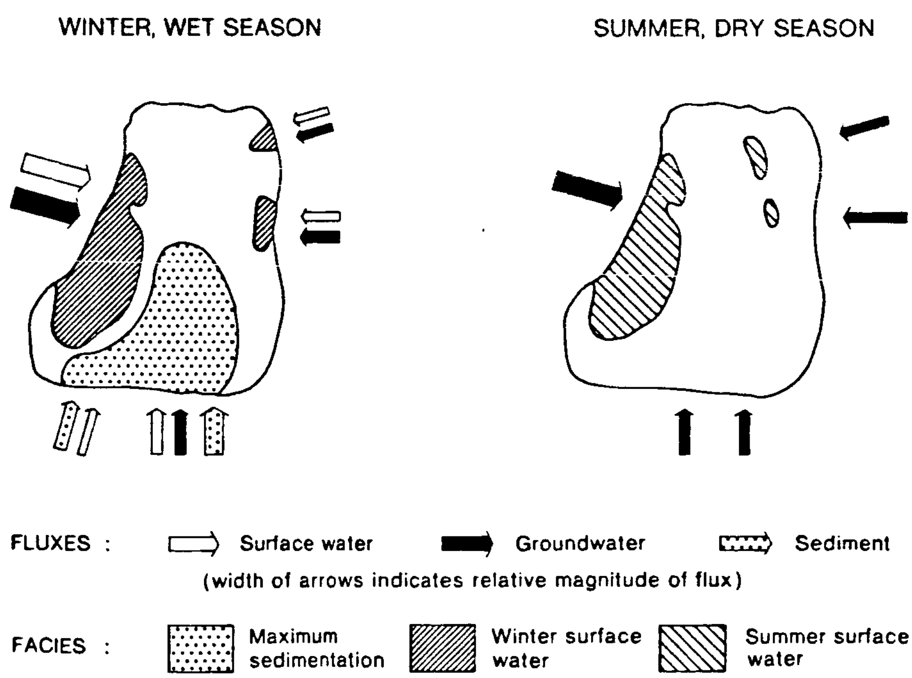
RATIO IMAGE (SEP 1985,JAN 1983)
Median Filtered

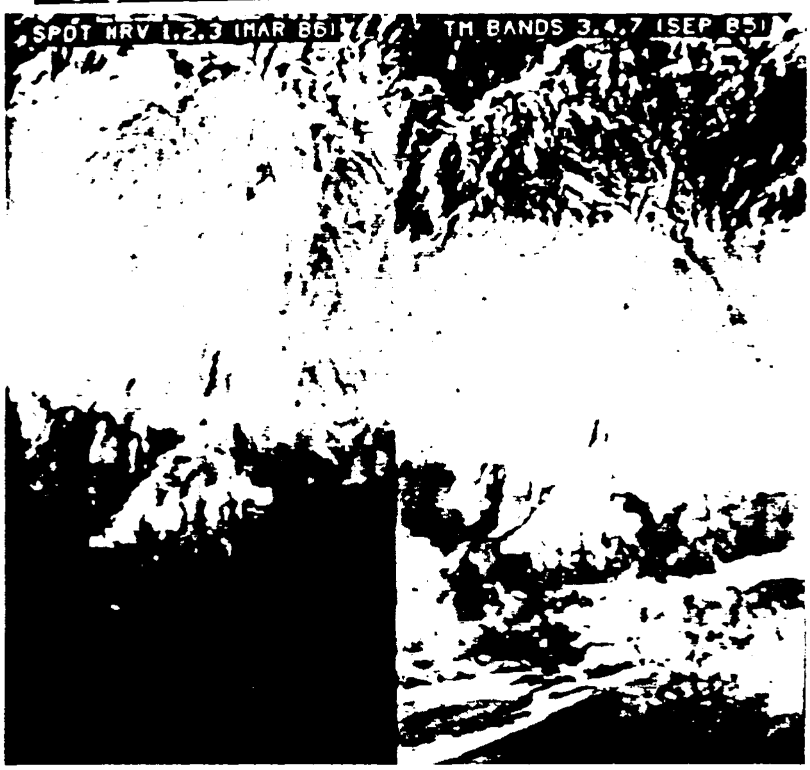



P. C. 3 (DEC 83,DEC 81)


Djebel Orbata
ALLUVIAL FANS
EL GUETTAR OASIS
O. es Sadd
CHOTT
EL
GUETTAR
O. el Rahr
Djebel
Mdilla
KEY
Fan delta
Surface water collection areas
Permanently moist
Seasonally moist
Ridge of sediment
0
5
10 km.


WINTER, WET SEASON
SUMMER, DRY SEASON
FLUXES :
Surface water
Groundwater
Sediment
(width of arrows indicates relative magnitude of flux)
FACIES :
Maximum sedimentation
Winter surface water
Summer surface water


D
C
A
B


SPOT HRV 1,2,3 (MAR 86)
TM BANDS 3,4,7 (SEP 85)


SEBKHA EL HAMMA MSS FCC (DEC 81)
EH


SPOT HRV 1,2,3 6/3/86
CHOTT DJERID , TUNISIA